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Unmanned Aerial Vehicle Dropsondes with Global Positioning System Windfinding

by J. Cogan
Battlefield Environment Directorate

T. Greenling
S.A. Luces
J. Thomas
Physical Science Laboratory

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J. Cogan (ALR/BED)
T. Greenling, S. A. Luces, J. Thomas (PSL)

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New Mexico State University
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Detailed, quantitative, atmospheric data are essential for accurate analyses and forecasting of mesoscale phenomena for military and civilian applications. Over remote areas, environmental satellites provide qualitative and broadscale quantitative information more suitable for synoptic scale analyses. Because satellite instruments for measuring atmospheric variables have relatively large footprints and vertical resolutions, airborne systems remain the only reliable source of detailed, quantitative, accurate data for remote mesoscale areas, especially 500 by 500 km or smaller. Within remote or hazardous regions, use of manned aircraft for gathering atmospheric data may not be feasible because of the high risk to personnel and expensive equipment. Unmanned aerial vehicles can carry small sensors and dropsondes into these areas, at no risk to personnel and at a very low cost. The Battlefield Environment Directorate of the Army Research Laboratory led the development of a dropsonde with Global Positioning System (GPS) windfinding capability, assisted by the Physical Sciences Laboratory of New Mexico State University. This report briefly discusses the dropsondes and presents the results of the flight test at the conclusion of phase 1. Phase 1 investigated current off-the-shelf capability (as of late 1994) with a modification to obtain wind profiles via GPS techniques. Plans include a phase 2 that will seek to produce proof-of-concept prototype dropsondes and dispenser.

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Executive Summary

Detailed, quantitative, atmospheric data are essential for accurate analyses and forecasting of mesoscale phenomena for military and civilian applications. Over remote areas, environmental satellites provide qualitative and broad-scale quantitative information more suitable for synoptic scale analyses. Because satellite instruments for measuring atmospheric variables have relatively large footprints and vertical resolutions, airborne systems remain the only reliable source of detailed, quantitative, accurate data for remote mesoscale areas, especially those around 500 by 500 km or smaller. Within remote or hazardous regions, use of manned aircraft for gathering atmospheric data may not be feasible because of the high risk to personnel and expensive equipment. Unmanned aerial vehicles (UAVs) can carry small sensors and dropsondes into such areas, at no risk to personnel, and at a very low cost. The U.S. Army Research Laboratory, Battlefield Environment Directorate led the development of a dropsonde with Global Positioning System (GPS) windfinding capability, assisted by the Physical Sciences Laboratory of New Mexico State University.

Weather conditions at different altitudes, for a given location, can be measured by radar techniques, a rawinsonde carrying data collection equipment aloft, or dropping a parachute suspended package (dropsonde) from an aircraft. Wind speed and direction of a sonde are calculated by direct tracking, or with the aid of the OMEGA, LORAN, or GPS radio navigation systems, by measuring time and location. Several models of GPS receivers or engines will acquire, track, and process the GPS coarse acquisition code and navigation information. The navigation accuracy of the GPS engine has a statistical distribution that depends on the error in the range signal caused by selective availability and the geometry or relative positions of the satellites and the receiver. A three-dimensional navigation solution can be computed when the GPS engine is tracking at least four satellites.

This report briefly discusses the dropsondes and presents the results of the flight test. We concentrate on wind velocity measurements because GPS windfinding was the primary innovation. The results indicate that current technology dropsondes updated with GPS windfinding technology are capable of producing atmospheric soundings with an accuracy at least comparable to that from rawinsondes. The 600-m smoothing (similar to that of the rawinsonde system) gave values that fell mostly between the earlier and later rawinsonde flights. The UAV dropsondes and sensors will provide important

input for the Integrated Meteorological System and other projected Army systems. Other Department of Defense and civilian users can use this type of data for any application in which detailed in-situ data are required from remote areas over land or sea, where personnel could be at risk. Examples include regions in and around forest fires, near or over spills of hazardous materials, or through regions containing chemical or biological agents. For civilian applications in which personnel are not at risk, light, manned aircraft could carry onboard sensors and dispense dropsondes. The cost is expected to be low enough that agencies and others (such as universities) with limited resources can use these instruments.

1. Introduction

Detailed, quantitative, atmospheric data are essential for accurate analyses and forecasting of mesoscale phenomena for military and civilian applications. Over remote areas, environmental satellites provide qualitative and broad-scale quantitative information (cloud amount and type) and supply quantitative input more suitable for synoptic scale analyses (temperature and dewpoint soundings for standard atmospheric levels). However, satellite instruments for measuring atmospheric variables have relatively large footprints and vertical resolutions (Miers, Cogan, and Szymber 1992). For remote mesoscale areas (Orlanski 1975), especially 500 by 500 km or smaller, airborne systems (on-board or ejected) remain the only reliable source of detailed, quantitative, accurate data. Skony, Kahl, and Zaitseva (1994) provide an example of older technology dropsondes ejected from large, manned aircraft over a remote area. Within remote or hazardous regions, the use of manned aircraft for gathering atmospheric data may not be feasible because of the high risk to personnel and expensive equipment. Unmanned aerial vehicles (UAVs) can carry small sensors and dropsondes into remote or hazardous areas without degrading other missions, at no risk to personnel, and at a very low cost. The U.S. Army Research Laboratory, Battlefield Environment Directorate led the development of the dropsonde discussed in this report, assisted by the Physical Sciences Laboratory (PSL) of New Mexico State University.

Weather conditions, at different altitudes, for a given location can be measured by radar techniques, a rawinsonde carrying data collection equipment aloft, or dropping a parachute suspended package (dropsonde) from an aircraft. Wind speed and direction of a sonde are calculated by direct tracking or, with the aid of the OMEGA, LORAN, or Global Positioning System (GPS) radio navigation systems, by measuring time and location. The development of GPS has provided a means of increasing the accuracy of wind speed and direction measurements. GPS eventually will replace OMEGA and LORAN as they are phased out. Several models of GPS receivers or engines will acquire, track, and process the GPS coarse acquisition code and navigation information. The navigation accuracy of the GPS engine has a statistical distribution that depends on the error in the range signal caused by selective availability (SA) and the geometry or relative positions of the satellites and receiver. A three-dimensional (3-D) navigation solution can be computed when the GPS engine is tracking at least four satellites.

This report briefly discusses the dropsondes and presents the results of the flight test at the conclusion of phase 1. For more details on the specific dropsondes and flight test, refer to Greenling, Luces, and Thomas (1995). Phase 1 investigated off-the-shelf capability (as of late 1994) with a modification to obtain wind profiles via GPS techniques. Phase 2 seeks to produce proof-of-concept prototype dropsondes and dispenser. In this report, we concentrate on wind velocity measurements because GPS windfinding is the primary innovation.

2. Phase 1 Test and Results

The flight test took place on 14 Dec 1994 at White Sands Missile Range (WSMR), NM. Two types of sondes were tested, one built from commercial parts by PSL and one built by Radian, Inc. Both sondes used GPS techniques to obtain wind speed and direction and standard methods to obtain temperature, pressure, and humidity. The variables were recorded when the sondes were dropped from an altitude of approximately 3660 m (12,000 ft) above mean-sea-level (MSL).

2.1 Radian Dropsonde

The Radian dropsonde prepared for this test was a small, tubular prototype that had a Trimble SVeeSix-CM2 GPS engine and antenna integrated with Radian's LORAN board. The board was modified to use GPS information coming from the Trimble engine instead of computing its location using the LORAN radio signals. Several parameters in the sonde can be set and commands can be sent to the GPS engine via a connector on the module. The sonde transmits the GPS, and pressure, temperature, and humidity (PTH), information to the ground station through a flexible wire antenna. The antenna is stowed with the dropsonde parachute in the top of the tubular structure. When the parachute deploys, the antenna is extended to its operational position by the parachute shroud line. GPS and PTH data are transmitted using direct digital modulation of the 403-MHz carrier with 1-kb/s encoded data. A ballute parachute is used to slow the descent of the sonde. A single shroud line connects the parachute to the top of the sonde. The vertical length of the parachute is about 84 cm and the horizontal section (measured diagonally) is 94 cm.

A portable computer, battery, GPS antenna, GPS receiver/control box, and acquisition tube are used to prepare the dropsonde before it is dropped. This equipment is used so the Trimble GPS engine will acquire the GPS signals and go into a 3-D navigation mode quickly after the sonde is dropped from an aircraft. The antenna must be mounted outside the aircraft to receive the GPS signals. The acquisition tube contains another antenna that retransmits the signals received by the external antenna. The GPS receiver/control box transfers up-to-date time, initial position, and almanac data to the GPS engine of the dropsonde.

The Radian ground station consists of an antenna, receiver, and computer. The receiver/frame buffer decodes the telemetry data from the sonde and stores (buffers) the data in frames consisting of 16 data words. Frame rate from the sonde is four frames/s, resulting in 64 words/s. Each word is a 16-bit quantity encoded as four ASCII hexadecimal digits. Sensor data are received in a raw uncorrected format to reduce the processing load on the sonde. A 16-bit time tag is added by the frame buffer to each frame to provide unambiguous lost frame detection. The receiver sends each frame of data to the computer where it is stored for postprocessing. Commands can be sent to the receiver to control the receiver frequency and other parameters.

2.2 PSL Dropsonde

PSL constructed a dropsonde using a Rockwell Microtracker GPS engine, microcontroller board, Vaisala RS80-15 radiosonde, and Aeroantenna Technology GPS antenna. Specifications may be found in the manufacturers' literature. The design concept in building the sonde was to buy off-the-shelf modules and minimize custom designs. Components were assembled in a tier structure and slid into a cardboard tube 10 cm in diameter by 51 cm in length. The complete sonde with parachute weighed 1.45 kg.

An assembly language program was written to command the Microtracker, record navigation data, and transmit the desired information. The navigation information is stripped out and retransmitted to a ground station. The Microtracker sends frames of navigation and status information with a message identifier over a serial receiver at 300 Bd using Vaisala's 403-MHz carrier. A total of 52, 8-b bytes are sent to the ground station from the dropsonde. The Microtracker provides navigation data once a second, but data are transmitted every three seconds because of the low baud rate. In addition, PTH data are sent to the ground station on the 403-MHz carrier via a quarter-wave wire dipole antenna extending out of the bottom of the dropsonde during descent.

The sonde is built so the Microtracker can be switched to standby (keep-alive) or normal operation mode. In normal operation mode, the Microtracker tracks the GPS satellites and transmits navigation telemetry data to the ground station. In

standby mode, only the internal clock of the Microtracker is incremented, and the last sets of satellite parameters are maintained in static random-access memory. The stored satellite parameters allow a rapid navigation fix when the sonde is switched to operate mode, if the age of the parameters is less than 4 h. The GPS antenna of the dropsonde is mounted at the top of the tube, and the parachute is folded over the antenna. The parachute has a cross type configuration with eight shroud lines and a length of approximately 152 cm across each section of the cross. The dropsonde operation consists of acquiring and tracking GPS satellites while on the ground, switching the GPS engine to standby mode, and taking the sonde aloft in the aircraft. At the desired test altitude, the GPS engine is switched to normal operation mode, and the sonde is dropped from the aircraft.

The ground station consists of a Vaisala Digicora MW11 radiosonde receiver, two computers, a modem, and a Rockwell Microtracker. The Digicora receives and demodulates PTH and GPS data. PTH data are recorded on one of the computers via a serial communications port. A sample of the demodulated frequency modulated signal is sent into a modem that decodes the 300-Bd GPS data and sends them to the second computer. The second computer also receives GPS information from the Microtracker in the ground station.

The PSL ground station uses a modified version of the software supplied with the Rockwell Microtracker development kit to display and record the received GPS information. The modified software decodes the ground station GPS data and the dropsonde telemetry data, then produces a real-time display as shown in figure 1. In figure 1, the dropsonde data are in the lower box. The state and space vehicle identification (SVID) numbers for each channel (CHAN) of the two receivers are shown in the upper box. The SVID number represents the satellite being tracked on the indicated channel, and a state 5 indicates the CHAN is processing the satellite ranging data. An asterisk next to a CHAN number indicates the channel is being used as a utility channel. The utility channel acquires and cycles through the satellites in view that are not being used to compute the 3-D navigation solution. As shown, only space vehicles 14, 22, 29, 25, and 15 are in view of the antenna. The latitude, longitude, height, speed, and heading of the antenna are also shown. When this figure was made, the sonde and ground station antennas

```
                              DropMon v1.02
                                                                    MAIN MENU OPTIONS
Mode: 3D NAV        Set Time =        23897
FOM   =       1    *Time     = 18:27:42.162
Sats Used=    4     Date     = Sun 01/29/1995                        F1: Time Init
PDOP  =    2.78     GPS Time     66472.163                           F2: Position Init
GDOP  =    3.13     GPS Week =          786                          F3: Mask Angle
                                                                     F4: Datum Select
Lat, Long, Height=     N32° 16.7081'  W106° 45.2190'  1170.1         F5: Set Altitude
Speed, Heading    =           1.11 MPH          323.21°              F6: Auto 2D
                                                                     F7: Cold Start
CHAN  SVID  STATE   C/No | D-SVID  D-STATE | SV   EL    AZ           F8: B.I.T Test
CH1    14     5      39  |   22       5    | 14  69.3 290.0          F9: Store Almanac
CH2    22     5      39  |   14       5    | 22  57.5 115.6         F10: Load Almanac
CH3    25     5      43  |   25       5    | 29  39.7 313.4
CH4    15     5      36  |   15       5    | 25  30.3  46.8           N: Next Menu
CH5*   29     5      38  | * 29       5    | 15  16.0 216.5         ESC: Quit
                                                                      R: Reset
Drop GPS Time =        66468.913                                      C: Clear CRT
Battery Voltage =  9.023                                              S: Screen
Drop Status   3D NAV
Lat, Long, Height=     N32° 16.7096'  W106° 45.2214'  1166.7
Speed, Heading    =           0.64 MPH          328.13°

                                                                  Ack: Mess 201
```

Figure 1. PSL ground station computer display.

2.3 Dropsonde Test

For the flight test, a helicopter rigged with a PVC tube and test computer was used to take the sondes to an altitude of about 3660 m (12000 ft) MSL, 2440 m (8000 ft) above ground level. Each sonde was inserted into and then dropped through the tube so its parachute would deploy below the helicopter. Two Vaisala rawinsondes were launched from a site a few hundred meters horizontally from the drop location.

The first rawinsonde was launched at 1554 universal time coordinated (UTC), before the helicopter arrived. The second rawinsonde was launched at 1820 UTC at the completion of the dropsonde tests. Data from each rawinsonde were used for comparison to the dropsonde information. Fisher et al. (1987) discuss accuracies of a number of rawinsonde systems. In addition, wind profiler data measured by the WSMR Atmospheric Profiler Research Facility

(APRF) were taken for comparison with the other instruments. Hines et al. (1993) describe the APRF and discuss its capabilities.

The first Radian sonde was programmed and dropped from the helicopter but did not transmit usable information to the ground station. We believe the parachute did not deploy, based on the large number of telemetry check-sum errors received by the ground station receiver and because of the damage to the sonde when it hit the ground.

A PSL sonde was dropped at approximately 1721 UTC or 1021 local time, and hit the ground 5 min and 7 s later. The received telemetry shows the Microtracker acquired the GPS satellites and went to 3-D navigation mode about 45 s after leaving the helicopter. There are 4 min and 22 s of usable GPS data from the sonde that start at the 3-D navigation mode and end when the sonde hit the ground. After hitting the ground, the sonde continued to transmit GPS and PTH data, with the Microtracker staying in a 3-D navigation mode most of the time, until recovered.

The final sonde dropped was a second Radian sonde. The second Radian sonde was dropped without being updated with fresh GPS parameters because of a procedural oversight, causing the sonde to take 143 s to acquire the GPS satellites and go to a 3-D navigation mode. The sonde was dropped at approximately 1730 UTC, acquired 3-D navigation at approximately 1733 UTC, and stopped transmitting at approximately 1736 UTC. The sonde transmitted good telemetry until it hit the ground. There are 2 min and 48 s of usable GPS data from the sonde, which start at the 3-D navigation mode and end when the sonde hit the ground.

2.4 Test Results

The following plots present the results of the flight tests. Figures 2 through 5 contain raw wind data from the two dropsondes. To best compare the results of the different wind measurements, it was necessary to smooth the data to reduce the effect of noise. Figures 6 and 7 show PSL dropsonde data with only three-point running averages applied. The averaging is performed as follows: given data points A, B, C, the new averaged data point is $B_{avg} = (A + B + C)/3$. One source, the rawinsonde "truth," is already smoothed within the receiver when it receives

and saves the data. The effect of the smoothing is to linearly fit the data in 600-m layers; therefore, the PSL dropsonde data were also linearly fitted in 600-m layers for comparison to the rawinsonde. As the smoothing interval increased, the dropsonde profiles more closely matched those from the rawinsonde. At the 600-m smoothing, the wind speed and direction nearly fit between the earlier and later rawinsonde values.

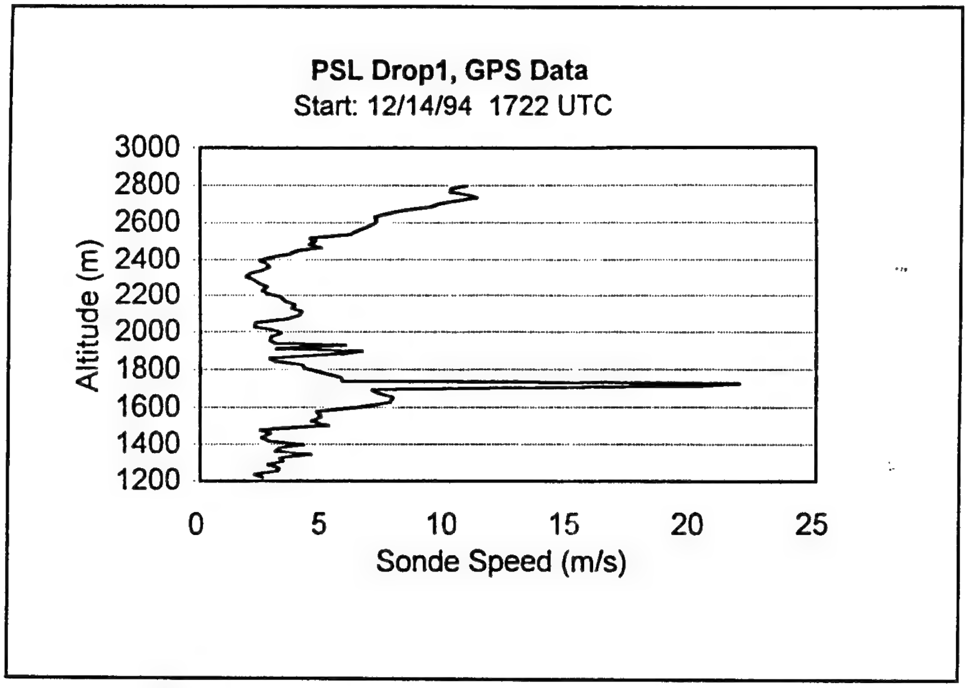

Figure 2. PSL dropsonde raw data, sonde speed versus altitude.

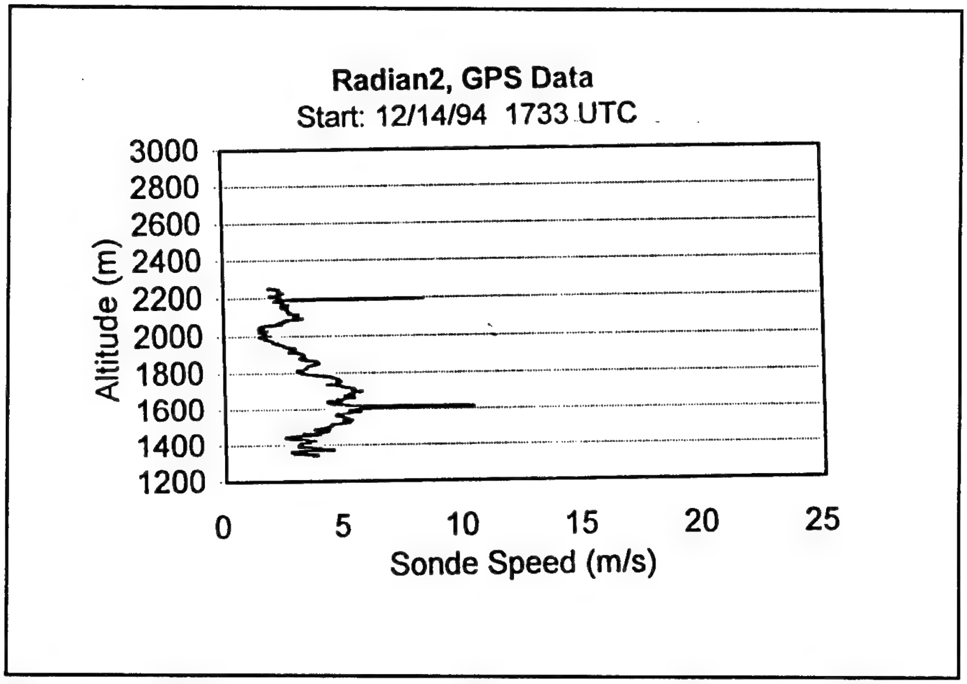

Figure 3. Radian dropsonde raw data, sonde speed versus altitude.

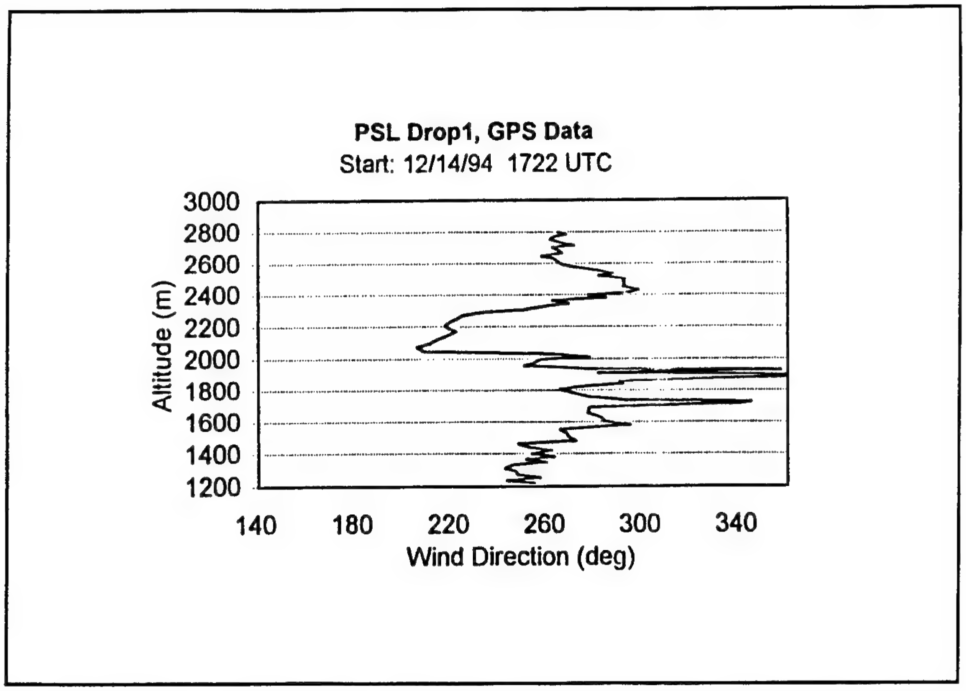

Figure 4. Radian dropsonde raw data, wind direction versus altitude.

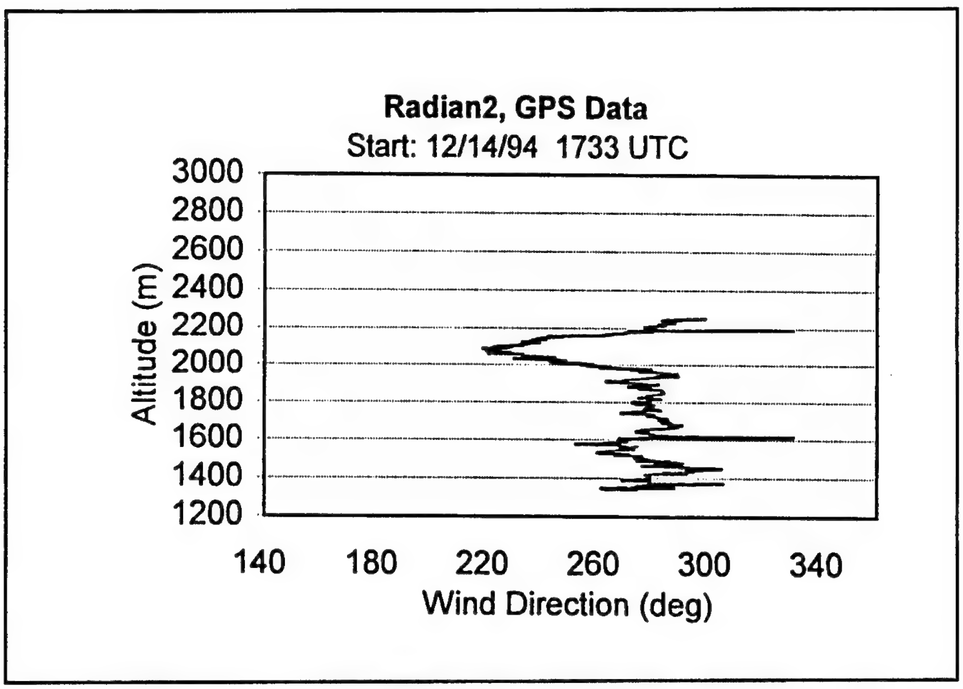

Figure 5. Radian dropsonde raw data, wind direction versus altitude.

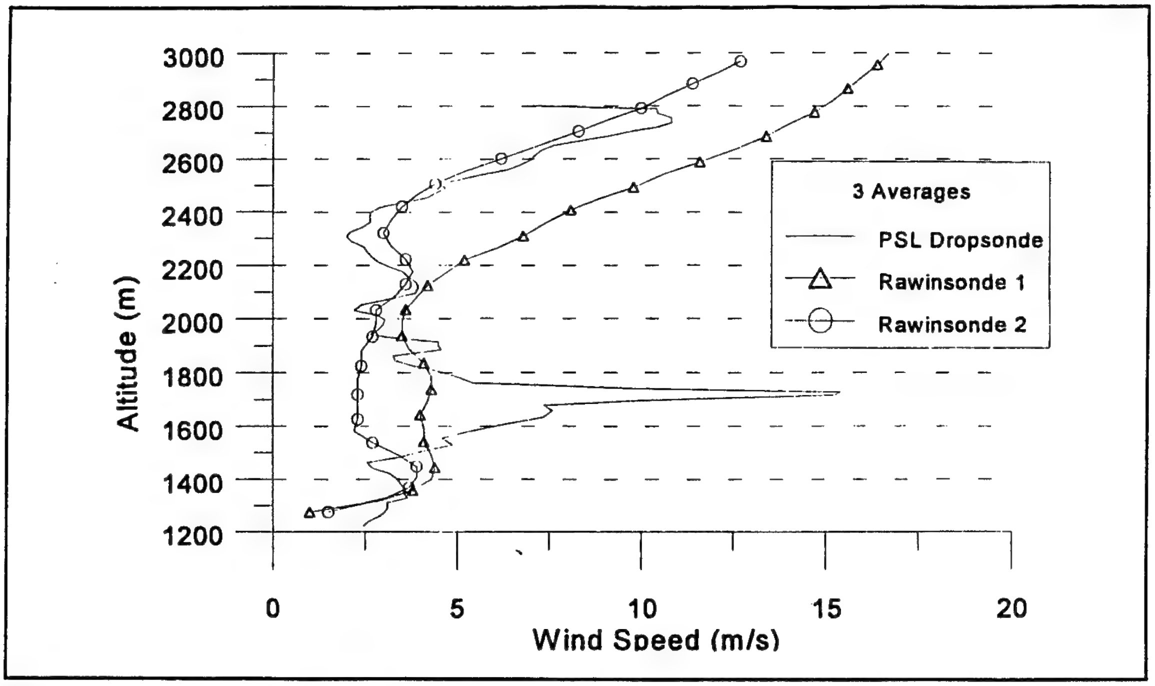

Figure 6. Comparison of PSL dropsondes to rawinsondes (speed, three -point averages).

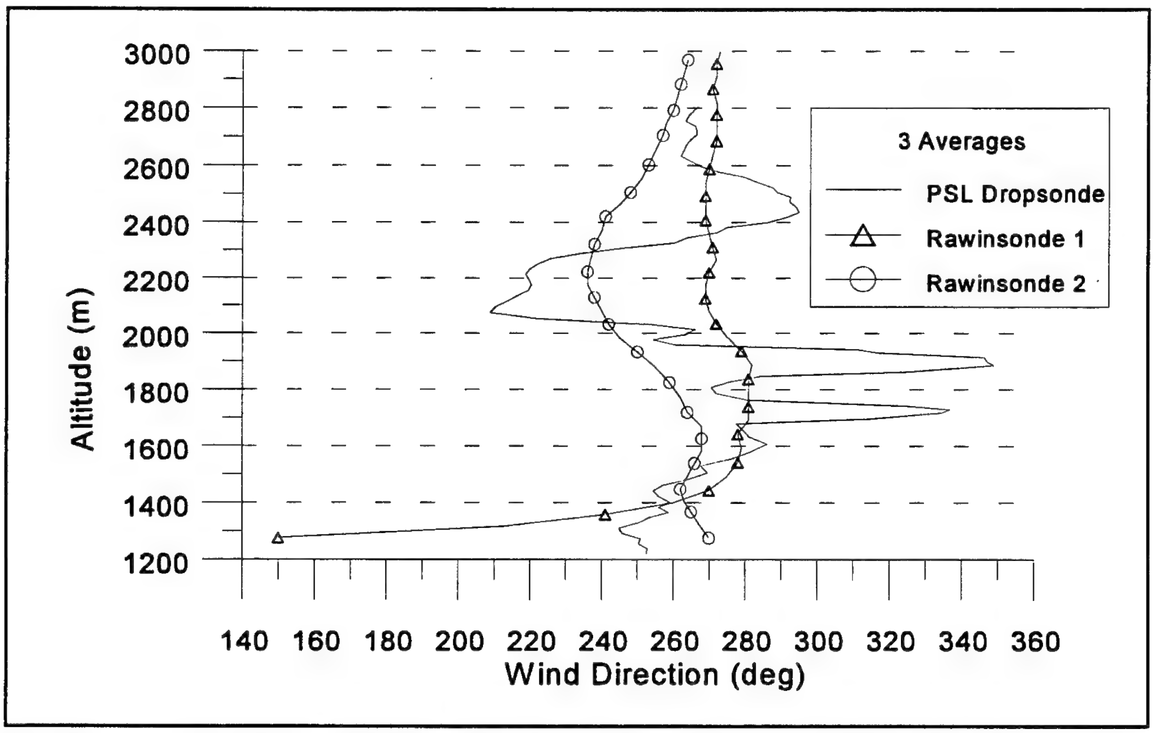

Figure 7. Comparison of PSL dropsondes to rawinsondes (direction, three-point averages).

The method of smoothing was as close to the method reported by the maker of the rawinsonde instrument (Vaisala) as possible (linear fit is made to the data over the layer required). All data outside the chosen confidence level (herein plus or minus one standard deviation) were removed and replaced with the linear fit data. A linear fit is again produced and used in place of the original data. Figures 8 through 13 compare rawinsonde profiles with dropsonde profiles smoothed in 250- and 600-m (PSL only) layers. Limited comparisons with hourly consensus average profiles of wind speed and direction from the APRF (not shown) yielded larger differences, at least in part a consequence of horizontal separation of about 18 km, the different type of measurement, and the temporal smoothing inherent in hour-long consensus averages. Finally, figures 14 and 15 compare profiles from the PSL and Radian dropsondes, smoothed in 250-m layers.

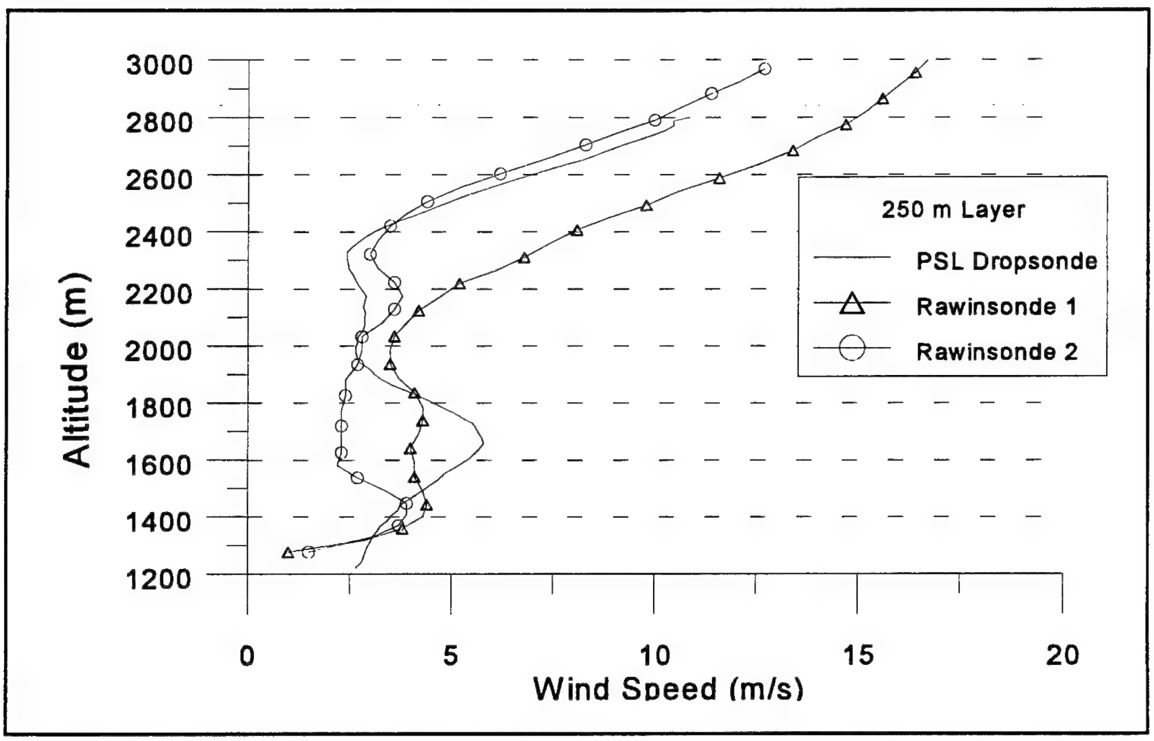

Figure 8. Comparison of PSL dropsondes to rawinsondes (speed, 250-m layer).

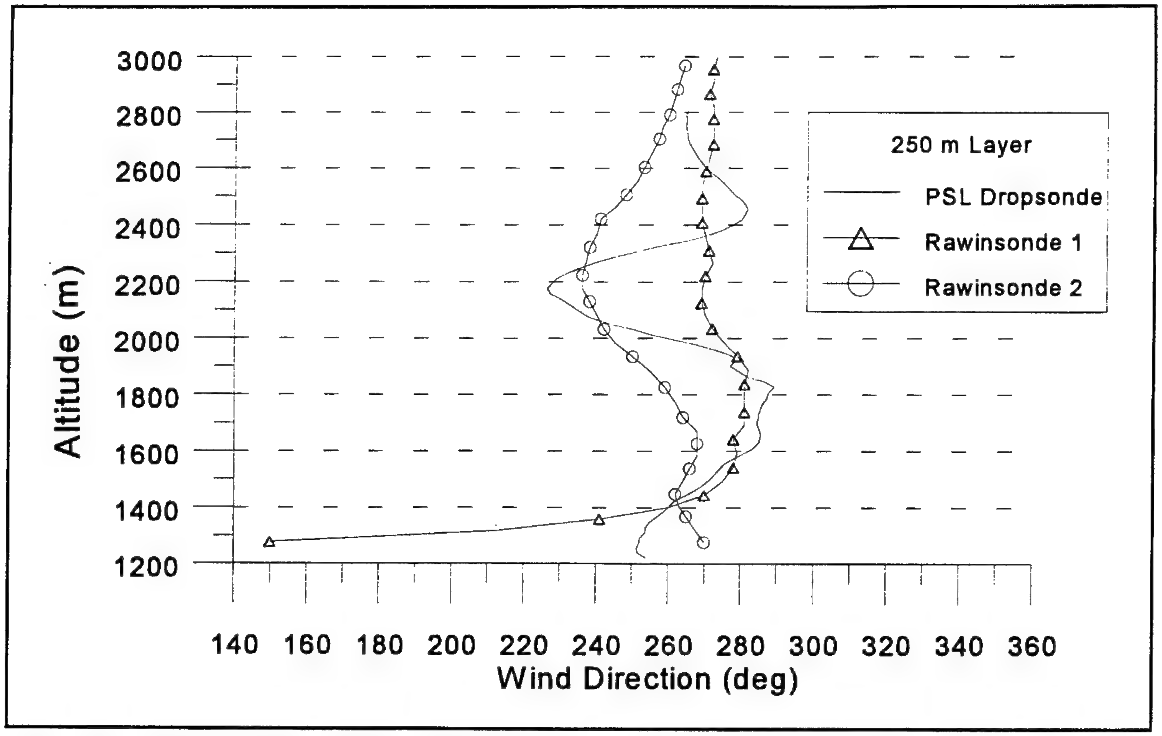

Figure 9. Comparison of PSL dropsondes to rawinsondes (direction, 250-m layer).

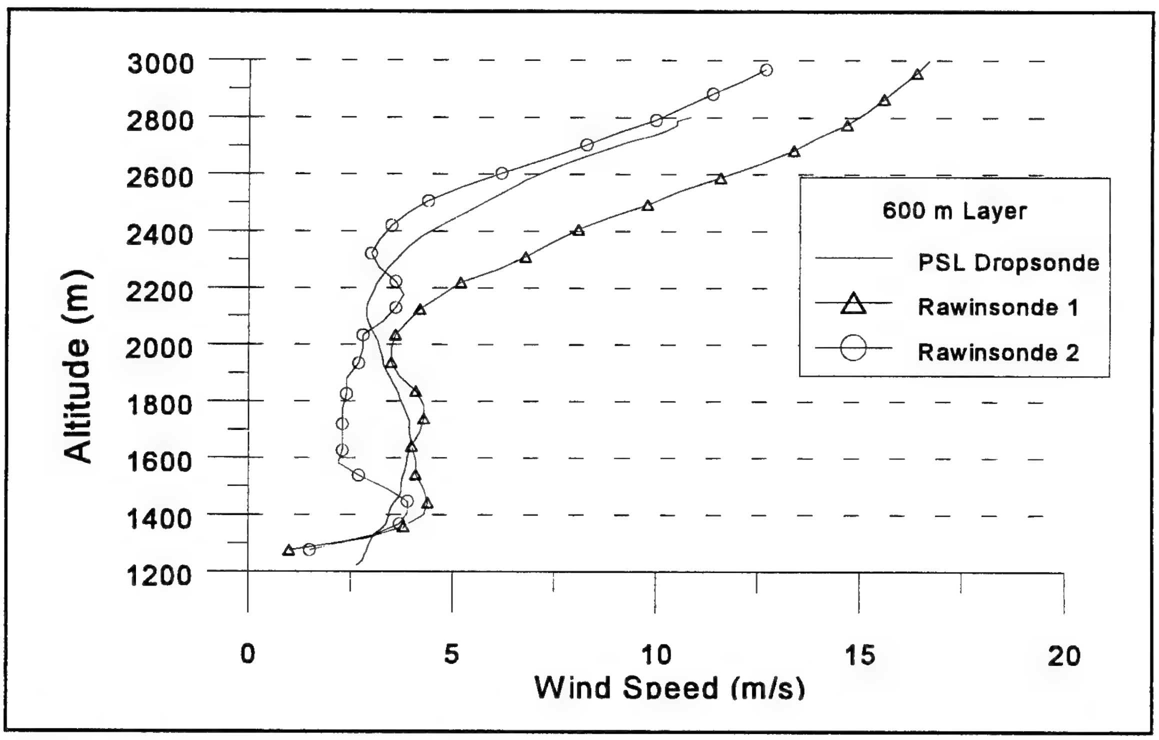

Figure 10. Comparison of PSL dropsondes to rawinsondes (speed, 600-m layer).

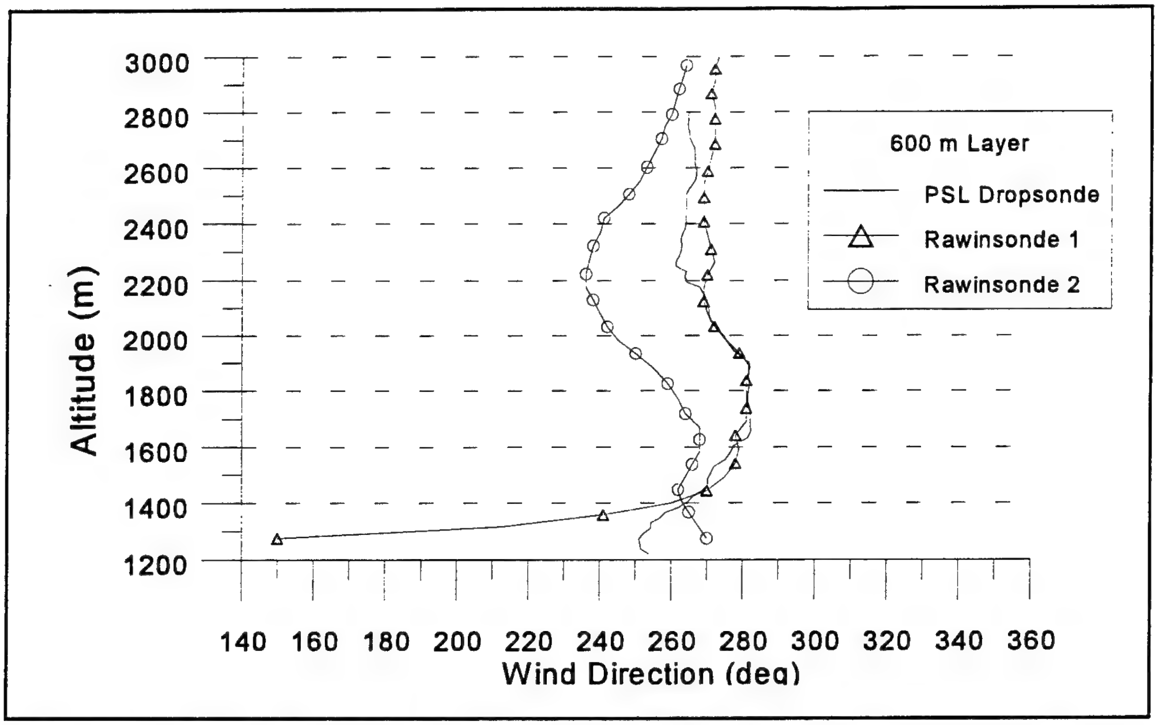

Figure 11. Comparison of PSL dropsondes to rawinsondes (direction, 600-m layer).

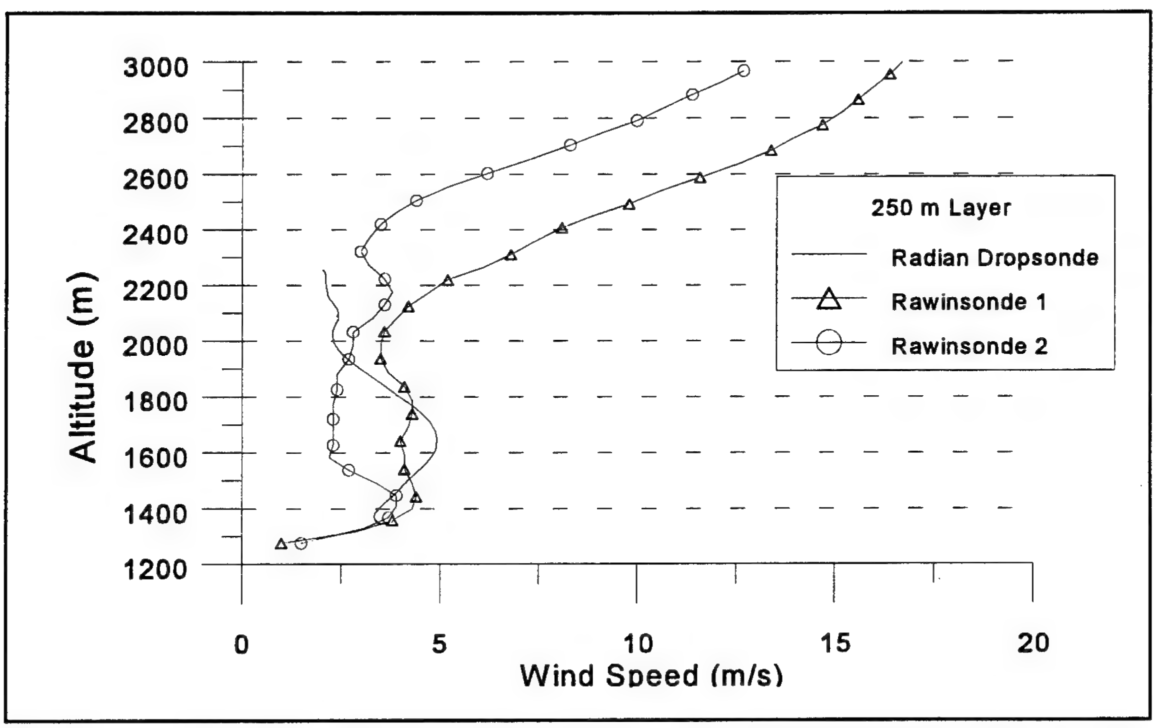

Figure 12. Comparison of Radian dropsondes to rawinsondes (speed, 250-m layer).

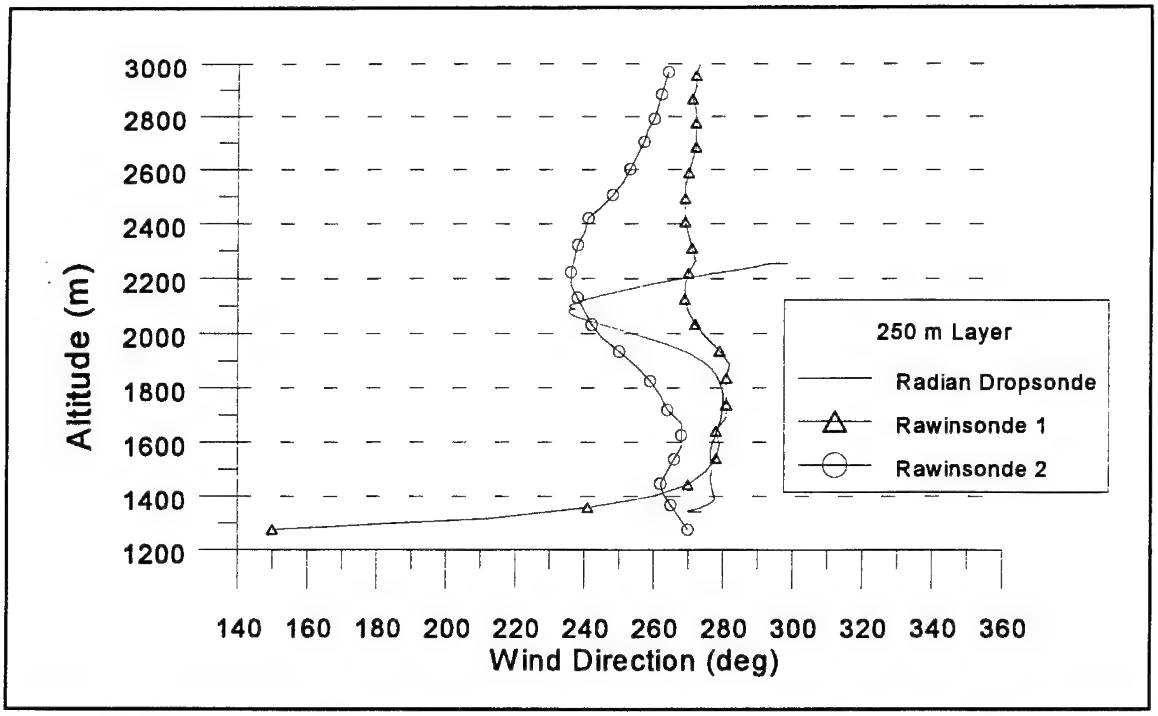

Figure 13. Comparison of Radian dropsondes to rawinsondes (direction, 250-m layer).

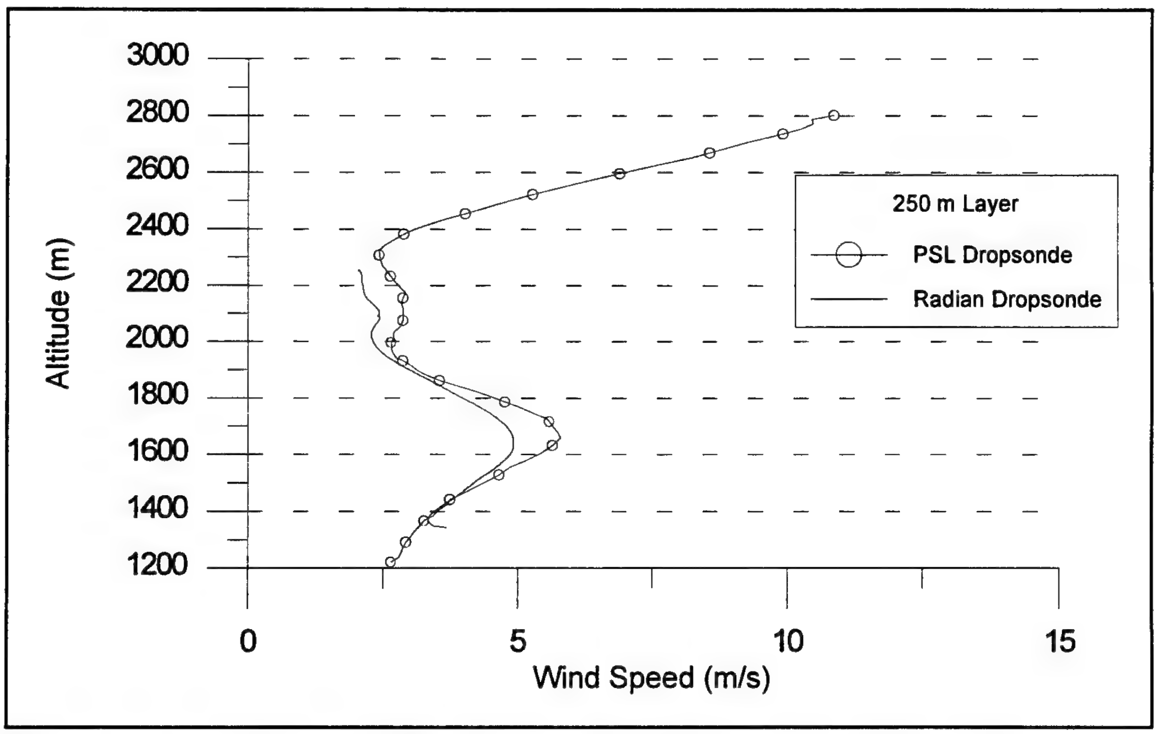

Figure 14. Comparison of PSL to Radian dropsondes (speed, 250-m layer).

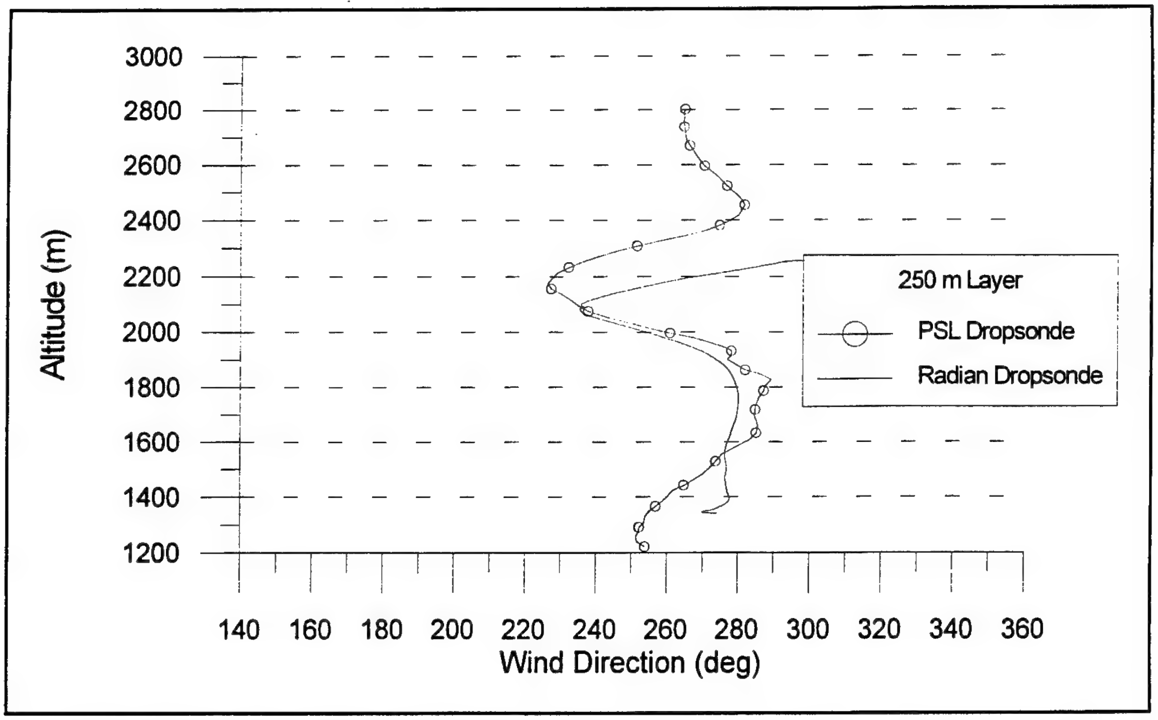

Figure 15. Comparison of PSL to Radian dropsondes (direction, 250-m layer).

3. Problems and Discussion

All upper-air sounding instruments appear to have some form of noise in the wind measurements. Rawinsondes are influenced by small eddy motions in the atmosphere and swinging motions of the package under the balloon; both are real effects but not significant to synoptic scale motion. Rawinsondes also have the problem of error caused by the method of measuring location (radio tracking, radar, or navigation aid). In addition, the balloon may not track the wind precisely as it rises because of the inertia of the system. Dropsondes suffer from all the problems of the rawinsondes. Luces et al. (1995) discuss wind measurement corrections for dropsondes in general. In this experiment, the noise source of interest is the error introduced into the GPS location finding, caused by the intentional SA errors. Wind profilers have their own set of noise sources (Wolfe et al. 1995; Cogan 1995).

The PSL and Radian receivers had interference with the reception of the GPS satellite signals after the electronic sections were assembled and placed into the respective cardboard tubes. Shielding was required around the GPS engines to stop the transmission of interference signals. Radian soldered metal covers over the Trimble GPS engine and telemetry transmitter section of the their LORAN board. The PSL sonde would not acquire any of the GPS satellites because of an interference signal coming from the GPS engine or Vaisala transmitter. The problem was corrected by wrapping the outer tube surface of the PSL prototype sonde with aluminum tape up to the GPS antenna.

The smoothed wind speed and direction data of the dropsondes are within the range of values given by the other accepted methods (rawinsondes and profiler). The majority of errors between the dropsondes and rawinsondes are caused by (1) the difference between position accuracy of LORAN and GPS radio-navigation systems, (2) different flight characteristics of the parachute and balloon, and (3) time and location differences between measurements. Some of the errors are correctable by applying differential (position) correction techniques and by developing flight dynamic correction factors to account for the differences between the parachute and balloon. GPS position fixes are normally more accurate than the LORAN computed position, and the update rate of the GPS data

in both dropsondes appear sufficient for an adequate representation of wind speed and direction. Radian's velocity update rate is every two seconds with altitude updated every 4 s, while PSL's velocity and altitude data are updated every three seconds.

Of the two methods used to prepare for dropping the sondes, PSL's is easier. Disadvantages in the PSL method are (1) the sonde must continually run on internal batteries or an external power supply until dropped from the aircraft, (2) the stored GPS information is time dependent, and (3) there is a time lag to reach the 3-D navigation mode after the sonde is dropped. The Radian preparation method benefits by allowing the dropsonde to be powered up shortly before the drop, conserving its internal batteries. In addition, when uploaded with up-to-date GPS parameters, the dropsonde should acquire and reach the 3-D navigation mode quickly after clearing the aircraft launch tube. Additional disadvantages are the requirement of several pieces of auxiliary equipment with an externally mounted GPS antenna, and the number of steps required to prepare the dropsonde.

4. Conclusion

The results from the phase 1 flight test indicate that current technology dropsondes updated with GPS windfinding technology are capable of producing atmospheric soundings with an accuracy at least comparable to that from rawinsondes. The 600-m smoothing (similar to that of the rawinsonde system) gives values that fall mostly between the earlier and later rawinsonde flights. The flight tests planned for the phase 2 dropsonde system will check the quality of a system designed specifically for UAV, which will require far less manual intervention. Coincident profiles (3- to 5-min averages) from the Mobile Profiling System (Cogan 1995; Wolfe et al. 1995) and nearly coincident rawinsonde launches will allow a thorough test and evaluation of the phase 2 system.

A successful UAV dropsonde system, combined with an onboard meteorological sensor package (Cogan et al. 1991), will be able to collect detailed atmospheric data over denied areas, along the flight path, and vertically at the dropsonde ejection locations. The UAV dropsondes and sensors will provide important input for the Integrated Meteorological System and other projected Army systems. Other Department of Defense and civilian users can use this type of data for any application in which detailed in-situ data are required from remote areas over land or sea, where personnel could be at risk. Examples include regions in and around forest fires, near or over spills of hazardous materials, or through regions containing chemical or biological agents. For civilian applications in which personnel are not at risk, light, manned aircraft could carry onboard sensors and dispense dropsondes. The cost is expected to be low enough that agencies and others (such as universities)with limited resources can use these instruments.

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Acronyms and Abbreviations

APRF	Atmospheric Research Profiler Facility
GPS	Global Positioning System
MSL	mean sea level
PSL	Physical Sciences Laboratory
PTH	pressure, temperature, and humidity
SA	selective availability
SVID	space vehicle identification
3-D	three-dimensional
UAV	unmanned aerial vehicle
UTC	universal time coordinate
WSMR	White Sands Misslile Range

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